Journal of Cleaner Production 212 (2019) 334–342

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

A photovoltaic net metering system and its environmental performance: A case study from Slovenia

Peter Virtič [a], Rebeka Kovačič Lukman [b, *]

[a] University of Maribor, Faculty of Energy Technology, Hočevarjev trg 1, SI-8270, Krško, Slovenia
[b] University of Maribor, Faculty of Logistics, Mariborska c.7, SI-3000, Celje, Slovenia

ARTICLE INFO

Article history:
Received 25 June 2015
Received in revised form
4 December 2018
Accepted 5 December 2018
Available online 5 December 2018

Keywords:
Net metering
Photovoltaics
Life cycle assessment
Case study Slovenia

ABSTRACT

Energy for society is an important element globally. Policy discussions in relation to climate change, suggest a transition from fossil-carbon-based systems to those based primarily upon renewable sources. The authors of this paper focused on a technical approach that can help to make that transition, namely pilot photovoltaic net metering installation for a business-residential entity in Slovenia, including its environmental perspectives. Results of the pilot photovoltaic net metering system installation revealed that the most cost effective solution is a photovoltaic installation with peak power of 6 kW, producing excess energy during the daytime. This has demonstrated that, with a proper planning, an optimum balance between energy production and consumption can be reached, and achieving a minimum price per kWh of the system. Regarding the environmental performance of the system, the results indicated that the most significant environmental impacts during its life cycle are related to global warming followed by human toxicity and terrestrial eco-toxicity. Photovoltaic net metering represents an option for producing and consuming cleaner energy, compared to conventional generation and usage, lowering the total price of the electrical energy (including fees and taxes) in comparison with the market purchases. This case study suggested that employing photovoltaic net metering in Slovenia is a reasonable option from the financial and environmental points of view, especially in the event of future increases of electricity price.

© 2018 Elsevier Ltd. All rights reserved.

1. Introduction

Energy issues are directly contributing to global challenges (UNDESA, 2013). A coherent and comprehensive approach towards energy and sustainable development was necessitated, fostering the change in consumption and production of energy patterns (Rocha et al., 2017). Decision fostering the development of RES are based on various aspects, such as reduction of greenhouse gas (GHG) emissions, reduction of the dependence of fossil fuels, secure and safe energy supply, and reduction of resource depletion (Abdin and Noussan, 2018).

Over the last decade RES usage has risen and has become a significant part of the energy mix in many countries, *e.g.* Norway 69.4% (up from 58.1% in 2004), Sweden 53.8% (up from 38.7% in 2004), Slovenia 21.3% (up from 16.1% in 2004), while the average of the EU-28 is 17% (up from 8.3% in 2004) (Eurostat, 2018). In Slovenia, electrical energy is produced in conventional power plants connected to the transmission grid and in dispersed small and micro power plants connected to the transmission and distribution grid. The following dispersed production in Slovenia is especially important:

- Small hydro power plants,
- Small photovoltaic (PV) power plants,
- Industrial facilities for combined heat and power (CHP)

Slovenian electricity production in 2015 amounted to 11,741 GWh, with 33.3% share of thermal power plants, hydro power plant 32.3% and nuclear power plant with 22.9%. 981 GWh of produced electricity is included in the support scheme for renewable energy sources (RES) and high efficient CHP. Total electricity energy consumption in Slovenia in 2015 was 13,905 GWh, representing 2.7% increase in a comparison to 2014 (Slovenian Energy Agency, 2016); 9.3% of the total installed is RES power (electricity), excluding hydropower and CHP with biomass (Slovenian Energy Agency, 2017). In 2015 Slovenia reached the share of 22%

* Corresponding author.
E-mail address: rebeka.kovacic@um.si (R. Kovačič Lukman).

https://doi.org/10.1016/j.jclepro.2018.12.035
0959-6526/© 2018 Elsevier Ltd. All rights reserved.

and by 2020 it has to achieve the 25% based on the commitment to the European Union. It can be clearly seen that the most important trigger to increase the share of RES was the introduction of feed-in-tariffs which were phased out by 2014. Considering RES in installed power, the fractions are following: landfill gas (1%), wind (1%), CHP – wood, biomass (3%), biomass (4%), biogas (7%), biogas (7%), small hydro (25%) and photovoltaic (59%), (Slovenian Energy Agency, 2017).

The European Commission has with the 2030 Energy Strategy set new targets for the EU until 2030 (European Commission, 2014). Based on commonly agreed policy directives, governments, interested in sustainable energy production processes, have been establishing policies to provide incentives for wider employment of RES (*e.g.* PV) (Radomes et al., 2015). Support schemes for investors are important because they foster and promote RES usage, especially through a reduction in energy production costs and increasing of selling price and energy purchase volumes (EP&EC, 2009). One such support scheme is the 'Feed-in-tariff,' (FIT), highlighted in the European Parliament and European Council directive from 2009 (EP&EC, 2009). This offers long-term contracts for guaranteed electricity purchases for RES producers, including subsidised electricity prices that are higher than the price paid by the consumer.

As reported by Koumparou et al. (2017) the most utilized support scheme was Feed-in Tariff (FiT), which represented a main development driver of new technologies for RES, such as photovoltaic (PV) systems, helping States to achieve politically set targets. PV installed capacity enormously increased in EU from 10,3 GWp in 2008 to 94,5 GWp in 2015. As further argued by Koumparou et al. (2017) and Couture et al. (2010) the FiT was commonly criticized regarding its feature of integrating the associated costs into the electricity rates of all consumers. In 2013 the European Commission (COM, 2013) suggested that Fit should be phased out and financial support for RES (including PV) should be limited to certain issues such as making RES competitive, fostering flexible support schemes and responding to the energy production costs. Many countries in Europe have abandoned FiT, and deployment of PV systems have dropped as well Koumparou et al. (2017). In Slovenia, the statistical data show that the share of PV electricity according to all electricity production decreased in 2016 due to the end of the FiT and new non-solar investments in electricity production, although the net metering scheme was launched and 266,8 MW of peak power was installed by 2016 (Slovenian Energy Agency, 2017). Also, the data from the EurObserv'ER (2017) indicated that the annual connected capacity of PV dropped by 22.7% compared to 2015. The main reason for decreased investment in PV systems is a discrepancy between energy demand and the availability of PV energy that has to be consumed immediately after production. If this is impossible, the energy has to be stored and this storage represents an additional component in the PV system at significant cost, thus demotivating private investors. The cost of such batteries for small scale producers or for neighbourhood storage is decreasing. Therefore, new models of interventions in RES have to be developed. For this reason, more effort towards harmonisation and re-evaluation of existing incentives is needed in order to achieve a faster PV technology uptake.

PV net metering, where the electricity grid represents virtual energy storage or better offers a possibility without compromising the interests of utilities and consumers. The main advantage of net metering is to produce renewable energy with its consumption occurring at the same location (Dufo-Lopez and Bernal-Agustín, 2015). Net metering represents an alternative scheme to FiT (Nikolaidis and Charalambous, 2017), where the key difference is that net metering works via retail tariffs, allowing customers to offset their electricity costs with the utilisation of their PV system (Nikolaidis et al., 2015). Unlike FiT, a net metering scheme does not need any financial support from the national budget for the investors if the price of electrical energy from the PV producer is lower than the price of electrical energy purchased from the grid. Net metering is an energy policy, where the entity (*e.g.* a household, company, …) is at the same time not only a producer, but also a consumer of cleaner energy. Such an energy-generating capacity of the entity has been identified as a "prosumer" (Fikru et al., 2018). When the produced energy by entity is greater as consumed, the surplus is fed into the grid and by deficit the energy is taken from the grid. After a certain netting period the difference between the produced and consumed energy is calculated. Depending on the net metering policy, different arrangements for surplus/deficit energies are possible (Watts et al., 2015).

Existing studies on net metering (discussed in the next section) include prevailing economic effects, consumer and policy issues, incentives and environmental performance, but not in the combination with new technologies. As argued by (Abdin and Noussan, 2018) a further consideration on sustainability related to the storage of the PV net metering is needed. Thus, the main goal of this paper was the development of an advanced technical solution regarding a pilot PV net metering system with an integrated controller, which enables various additional solutions, such as monitoring of consumer behaviour and/or implementations of smart micro grids as platforms for smart buildings and communities. Based on the measured energy production and consumption, by using this technical solution, the most appropriate installed peak power of the PV power plant was calculated. Furthermore, the study evaluated the net-metering pilot performance from the environmental perspective using a life-cycle assessment, in order to evaluate its global warming potential.

The rest of the paper is structured as follows: Section 2 represents literature review do draw a background and the context for the study, Section 3 introduces a case study from Slovenia, where the technical solution for the PV net metering was installed, monitored and implemented as well as the evaluation of environmental impacts for the technical solution, using life-cycle assessment, (LCA) and focusing on climate change issues, Section 4 represents the results of analyses of the PV net metering implemented and LCA calculated, followed by discussion in Section 5. Finally, conclusions and recommendations are included in Section 6.

2. Literature review

PV net metering as a policy incentive has recently received considerable attention, as it is a policy designed for fostering private investments in RES. Koumparou et al. (2017) argue that net-metering policy takes advantage of the grid parity situation and it is a step away from FiT, however, several policy variations make net-metering a complicated scheme. However, authors proposed in their study policy recommendations for the Mediterranean countries. Another comprehensive study was carried out by Nikoladis and Charalambous (2017), analysing the implemented policy in a case of Cyprus, providing insights and critical discussion on financial and policy implications. Dufo-Lopez and Bernal-Agustín (2015), showed a comprehensive methodology for the monetary assessment of the different policies of net metering and net billing for different countries. Both policies show PV net metering as a profitable system. The strategy behind the net metering is compensating costumers financially for electricity generated by their PV systems that is brought to the electricity grid (Oliva, 2018). PV net metering allows consumers to produce and self-consume electricity with minimal maintenance and no fuel costs, and has the potential to become a significant source of low-carbon electricity

(Strupeit and Palm, 2015).

Also, economic perspectives of the (PV) net metering have been extensively researched in the literature. Fikru et al. (2018) developed an economic model of net metering, representing a theoretical framework for understanding the relationship between energy generation, consumption, storage and the reliance on clean energy, where their findings suggested that the optimal reliance on solar energy depends on energy prices, income and the marginal energy storage costs. Similar findings were obtained by Ramírez et al. (2017), where authors provided a cost-effectiveness assessment with different combination of FiT and net metering schemes in selected EU countries, arguing that net metering is feasible, when upfront costs are low enough to make PV profitable or when electricity prices are high enough to balance the costs. Also, Yamamoto (2012) presented a comparative study of FIT and net metering, as well as Poullikkas (2013), carrying out a comparative assessment of net metering and FIT for residential PV systems, which identified that net metering performs better than FIT when the household electricity bill is taken into account. Camello and Reichelstein (2017) examined the effects of net metering restrictions, focusing on the impact of overage tariffs on the size of the residential PV investments, suggesting that if net metering were restricted such that the overage tariff was to be set at or above the levelized cost of electricity, there would not be a material impact on the volume of new residential solar installations.

Eid et al. (2014) investigated the consumer and economic effects of net metering, claiming that non-PV owners could find themselves unequal compared to PV owners, as they also had to pay higher charges for their electricity consumed to make up for netted costs of PV owners, thus the study presented effects on cross-subsidies and cost recovery. The consumer perspective was also discussed by Darghouth et al. (2014), who developing several scenarios, showing that the value of bill savings from net-metered PV is greater under time-varying rates than under the flat rate, due to the positive correlation between PV output and wholesale electricity prices in California.

Besides the policy and economic issues, the optimization of PV net metering has been investigated, *e.g.* Ratnam et al. (2015) considered a linear programming based approach for designing day-ahead battery charge and discharge schedules, when excess of electricity is compensated via net metering, Everly et al. (2017) exploring leveraging smart meter data for economic optimization, highlighting the necessity for implementing economic optimization for small-scale residential PV.

When considering environmental impacts, several studies were published about the LCA of PV (*e.g.* Stylos and Koroneos, 2014; Chen et al., 2016). Furthermore, Peters et al. (2017) provided a review of LCA studies on Li-Ion batteries, for stationary energy storage, with a focus on production processes of batteries, highlighting that 1 Wh storage is associate with 110 g CO_2 eq. However, the LCA for net metering was not perceived. The environmental analysis in this paper extends the work of previous authors, assessing the PV net metering system with a technical solution proposed in this study, from the environmental perspective, focusing on global warming potential.

3. Case study

Over several years in Slovenia, FiT has triggered the expansion of the PV market, with this being reflected in lower prices of PV technologies (Eurostat, 2015b). When considering our case study there is currently no expansion of PV system investments in Slovenia, although technology prices have dropped. Consumers still massively use electricity from the grid, with the energy mix including only 1.78% of PV. Taking into account the total costs of a PV power plant during its lifespan, the price of produced kWh of PV electrical energy in Slovenia has already dropped below the price of electrical energy from the grid including fees and taxes, therefore, PV power plants no longer need support from FIT and net metering can now present the possibility of cost-effective RES incorporation within the energy mix. In Slovenia net metering has not been used in practice yet, thus preliminary studies are needed.

A case study for the implementation of a PV net metering system and calculation of its environmental performance using LCA was conducted as a business-residential entity in Maribor, Slovenia. It was chosen on the basis of public requests, where a case with the smallest difference between installed peak power of the PV power plant and connection power for building consumption was selected. This was important because net metering policies require the consumption of the maximum possible share of produced energy at the location of production. The selection process was demanding because all the identified entities with PV power plants were based on the FiT scheme, where the goal of the investor was to build the biggest possible installation in order to have the highest profit possible.

The common characteristic of this case entity, established in the period of FiT, were: 14 kW of a connection power on the energy consumption side and 8.5 kW of peak PV power on the energy production side and net surface of floor area 223.1 m^2. It is important to highlight that the connection power of 14 kW is a common maximum connection (consumption) power of residential houses (in our case this was business-residential) that can be taken from the grid and is defined by standard fuses in three phases (3×20 A at 230 V of phase voltage). If the size (power) of the PV power plant is insufficient with less produced energy than the building needs, the difference has to be purchased on the electricity market at a higher total price. In contrast if the size of the PV power plant is oversized producing more kWh of electrical energy than the building needs, the surplus energy has to be sent/sold on the market at lower prices, which insufficiently covers the investment cost in an oversized PV power plant. Thus, the most cost effective size of a PV power plant in the scheme of net metering is the size where the produced energy is the same as consumed within a certain period (*e.g.* annually) and can be calculated by Eq. (1):

$$P_{\mathrm{PVopt}} = \frac{W_{\mathrm{cons}}}{W_{\mathrm{prod}}} P_{\mathrm{PV}} \tag{1}$$

where P_{PV} is the peak power of the existing PV power plant, P_{PVopt} is the peak power of an optimum PV power plant, W_{cons} is the annually consumed energy of the building and W_{prod} is the annually produced energy of the existing PV power plant.

3.1. A technical solution to pilot PV net metering installation

A technical solution of a pilot PV net metering installation with a remote data access and extensions was developed and implemented within the mentioned business-residential entity, including data analyses. During the development of the PV net metering system different data acquisition systems (off-the-shelf) were examined but none of them were able to cover all the requested specifications. Therefore, a new customised platform performing the desired functions and allowing expansions and upgrades was developed. This measurement platform was therefore, able to: connect various types of sensors; communicate via different protocols; perform real-time and parallel processing. It was very cost-efficient and small enough for the final implementation. From the consumer's perspective, this means that only one device is needed for simultaneous data processing from different sensors and metres instead of using several different

stand-alone devices.

A developed measurement platform uses a controller NI Single-board RIO®, which employs a reconfigurable embedded control and acquisition peripheral, real-time processor, a user-programmable field-programmable gate array (FPGA), an integrated circuit configured after manufacturing, representing the heart of the measurement system, which interacts with other devices. The measurement platform can interact not only with PV systems but also with household devices and the web in order to obtain all the relevant data for analysing the efficiency of energy production and its usage. It can also communicate and control different devices such as smart metres, PV inverters, data logger, household appliances, etc. as depicted in Fig. 1.

The measurement system's primary function is to obtain numerous data (temperatures, irradiance, power/energy consumption and production, voltage, current, etc.) process them and store them within different data formats using a time-stamp. In addition, the measurement platform has to be able to perform administrative functions (user access control, remote access, update software, interface with web and database server, etc.), to synchronise with Network Time protocol and provide options for controlling devices via digital input/output (I/O) or via communication protocols. It must also have a self-diagnostic test, handling errors and faults alarms, and validate and verify the received data (Virtič et al., 2014). In our case, an advanced PV net metering system with two electrical energy metres was developed and in addition to the measurement of produced, consumed and net energy, this also enabled simultaneous measurements of parameters such as solar irradiance, temperature of PV modules and temperatures of surroundings.

Fig. 2 presents a PV power plant of the business-residential house used as a case study. The solution of net metering system has to be attractive for the investors, meaning that it needs to be as cheap as possible, reliable, durable, repairable etc. should also be parameters that need to be in the equation, and therefore include only the minimum components necessary for adequate, durable, reliable functioning.

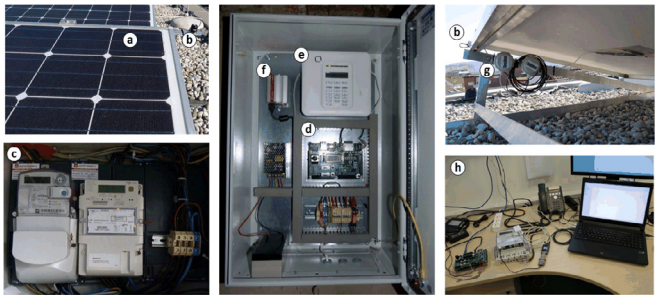

Fig. 2. PV net metering of a pilot business-residential entity (a – PV module, b – pyranometer, c – energy consumption and production metres, d – data acquisition and control board, e – base station for wireless temperature sensor, f – GPRS module, g – wireless temperature sensor, h – development phase of measurement platform).

3.2. Environmental performance of the pilot PV net-metering system

In order to define the PV net metering system from the environmental perspective, which was one of the objectives of our study, a life cycle assessment (LCA) was performed. The LCA is a holistic approach to system analysis and can be a useful decision-support tool regarding environmental concerns (Azapagic and Clift, 1999). According to ISO 14040 it is a technique that assesses the potential of environmental aspects and potential aspects associated with a product or service by compiling an inventory analysis, evaluating the potential environmental impacts, associated with inputs and outputs and interpreting the results of inventory analysis and impact phases (ISO, 2006a).

The LCA procedure consists of four steps: (1) Goal and scope definition (functional unit, system boundaries, assumptions and limitations), (2) Life-cycle inventory, (3) Life-cycle impact assessment and (4) Interpretation (ISO, 2006a). The LCA was carried out using the GaBi® Software (PE International, 2008) and Ecoinvent 2.1v database (Frishknecht et al., 2007). Based on the four steps procedure, the objectives, a functional unit, system boundaries as well as data sources, including main assumptions, were defined.

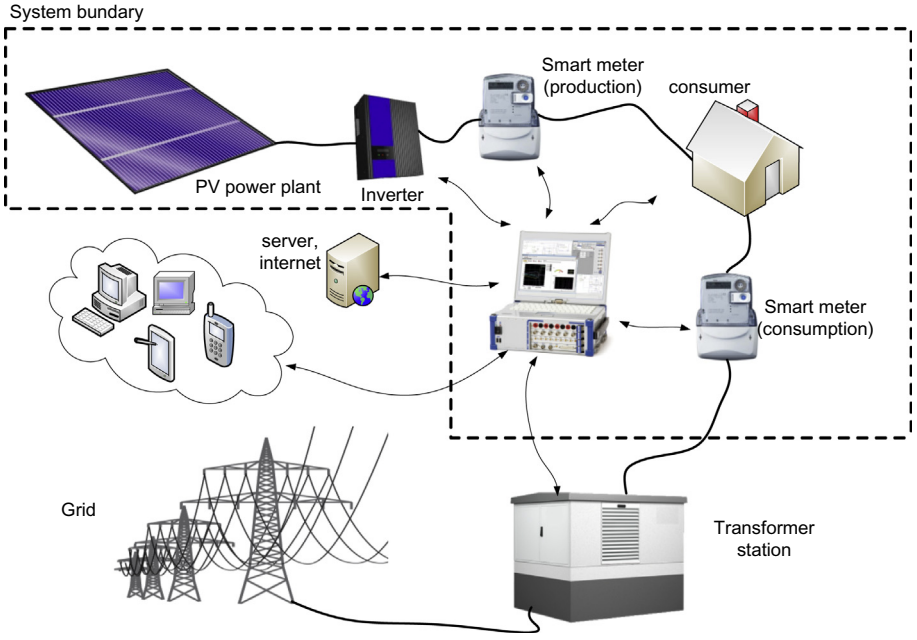

Fig. 1. A PV net metering system, a basic concept of measuring control systems for monitoring household PV system and its system boundary.

Therefore, the objective of the study was to estimate the life-cycle environmental impacts of the PV net metering, identifying parts of the system with the major environmental impacts. The environmental performance the PV net metering during the operational phase was compared with conventional energy, using energy mix in Slovenia.

The energy mix for Slovenia consisting of fossil energy (34.4%), nuclear energy (35.6%), hydro energy (29.5%), RES (0.2%) and waste energy (0.3%) (Dones et al., 2007), was extracted from the mentioned database (Ecoinvent 2.1v) as a process used and integrated within the GaBi® Software. The system under consideration was the PV net metering system, which was actually implemented within a pilot business-residential building with a net surface of floor area 223.1 m^2, in the city of Maribor (Slovenia), as shown in Fig. 1 (see system's boundary). A functional unit was set as "an annual production of energy (in kWh) needed for supporting daily activities at the test private-business of 223.1 m^2 investigated for this research in Slovenia." The phases considered were: manufacturing, utilisation, and end-of-life of the PV net metering. It should be noted that during the end-of-life phase the recycling of materials was taken as a more reasonable option due to the existing recycling practices in Slovenia. According to the Eurostat (2015a), Slovenia is a country that performs best when it comes to waste avoidance and recycling. Moreover, the system in the LCA was credited for materials' recovery, such as metals or plastics.

The primary data for the LCA study were obtained via *in-situ* measurements and by the producers of the PV net metering components (*e.g.* smart energy meter, controller). The secondary (LCA) data were sourced from the Ecoinvent database 2.1v, which was integrated into the GaBi® Software. The main assumptions were:

- Energy production: the energy production mix for Slovenia was taken from the Ecoinvent database.
- Recycling: it was considered that all the materials (plastics, metals) had been recycled and were based on those processes documented in GaBi® Software and for the mentioned materials the system had been credited.
- Other activities: transport and mounting of PV panels, including supplementary activities were excluded due the unavailability of the detailed data.

4. Results

In this section results of measured power (energy) consumption/production with newly developed technical solutions are presented, showing the matching of the energy production, demand and environmental impacts, when the surplus energy was used in the net metering scheme.

4.1. Measured results of the case study

In order to examine whether a total PV electrical energy production corresponds to the total energy consumption needs of the case study entity. Measurements at 15 min intervals of PV electricity production and consumption were performed from May 2014 to April 2015. Electrical energy consumption and PV electrical energy production profiles have been obtained for a specific period of year, presented in figures below. Each period includes the following months:

- Summer: June, July, August and September
- Transition period: March, April, October and November
- Winter: December, January, February and March

Fig. 3, Fig. 4 and Fig. 5 represent workday and non-workday consumption and production load profile. The workday consumption profiles during working hours show approximately half of the load of non-workdays at the same hours in all the seasons. A maximum daily production in the winter is approximately half of the summer production, while transition seasons have about 10% lower peak production than during the summer. It can be also perceived that during the load profiles are very similar for working and non-working days from 18.00 to 06.00.

Table 1 represents an average daily energy consumption and production in all the seasons for working and non-working days.

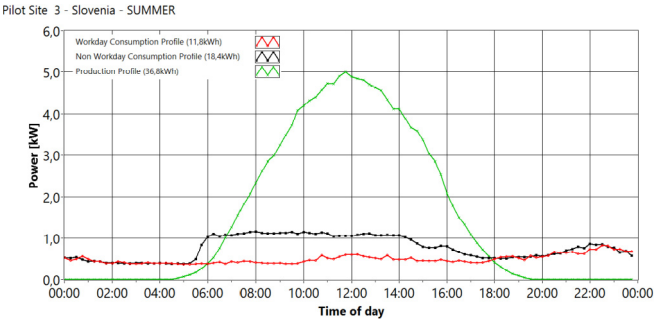
Pilot Site 3 - Slovenia - SUMMER
Workday Consumption Profile (11,8kWh)
Non Workday Consumption Profile (18,4kWh)
Production Profile (36,8kWh)
Power [kW]
Time of day

Fig. 3. Summer load profile for pilot site.

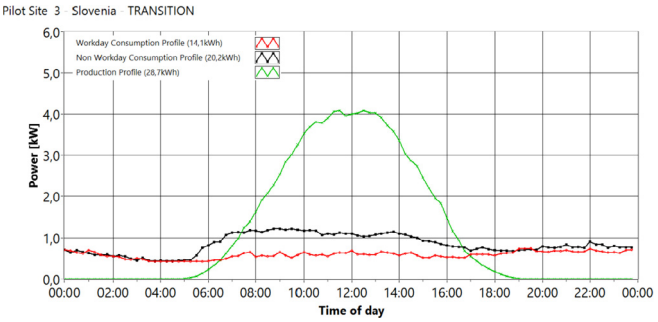

Fig. 4. Transition load profile for pilot site.

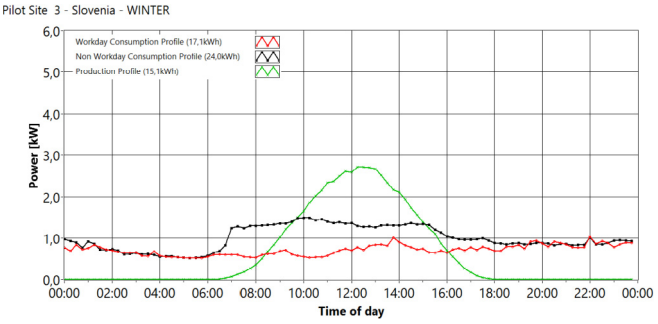
Pilot Site 3 - Slovenia - WINTER
Workday Consumption Profile (17,1kWh)
Non Workday Consumption Profile (24,0kWh)
Production Profile (15,1kWh)
Power [kW]
Time of day

Fig. 5. Winter load profile for pilot site.

Table 1
Average Daily consumed and PV produced energy.

Season	Consumption (kWh)		PV Production (kWh)
	Workday	Weekend	
summer	11.8	18.4	36.8
intermediate	14.1	20.2	28.7
winter	17.1	24	15.1

Energy consumption is significantly higher on non-working days meaning that the household activities with electrical devices require more energy than business activities in the offices with computers, air-conditioners and lights as the main consumers. It can be seen that the PV system of pilot site provide enough energy for the building needs, which is logical consequence of the FiT support scheme, where the highest possible size of PV installations was more important than optimum energy self-sufficiency.

Energy consumption and PV production of PV system with 8.5 kW of peak power in each month is presented in the following table.

Table 2 shows a more detailed power production and consumption, based on the measured electrical energy (15-min intervals), using two smart energy metres. This also shows the availability of PV electrical energy, which can be used directly for the consumption of the entity or sold to the grid. The reasons for relatively high off-peak power are running server and computers, which are often running 24 h a day, while other devices are on stand-by. From the measurements it can be seen from the data that the produced energy entirely satisfies the energy needs of the entity from about 7.00 a.m. to about 5.00 p.m., as produced energy within this timeframe is significantly greater than the electrical energy needs of the entity. However, this time period varies depending on the season and weather. Cloudy/rainy days for example do not provide such energy capture levels.

The produced electrical energy is 26.5 kWh/day and the consumed electrical energy is 18.7 kWh during an average per day. In the net metering scheme surplus energy is used by other consumers connected to the grid and for covering the energy losses, but from the prosumers' (producers and consumers at the same time) points of view the surplus energy is virtually stored in the grid. Using Eq. (1), the calculation of the more appropriate installed peak power of the PV power plant was documented for the case study entity as shown in Eq. (2):

$$P_{\mathrm{PVopt}} = \frac{W_{\mathrm{cons}}}{W_{\mathrm{prod}}} P_{\mathrm{PV}} = \frac{18.7}{26.5} \cdot 8.5 = 5.98 \text{ kW} \quad (2)$$

Considering the energy point of view and taking into account the average day of the year, the most cost effective solution for this case study unit in the PV net metering scheme is the PV power plant with the peak power P_{PVopt} of 6 kW.

4.2. The LCA case study results

The environmental impacts were calculated following the CML2001 impact assessment method (Guinée, 2002), using a method that restricted quantitative modelling to the early stages in the cause-effect chain to limit uncertainties (Thinkstep, 2015).

Table 2
Energy consumption and PV production (kWh).

Month	Consumption (kWh)	PV production (kWh)
April 2014	615	952
May 2014	481	1267
June 2014	480	1325
July 2014	529	1202
August 2014	428	1129
September 2014	494	713
October 2014	598	674
November 2014	620	321
December 2014	638	200
January 2015	728	275
February 2015	625	425
March 2015	659	907
April 2015	528	1237

The LCA results in Fig. 6 indicate that the more significant impacts from the case study PV net metering system are global warming potential (GWP) and human toxicity potential (HTP), followed by terrestrial ecotoxicity potential (TETP) and acidification potential (AP). Fig. 7 shows normalised environmental impacts, using normalisation factors for Europe 25 + 3 (Wegener Sleeswijk et al., 2008), where eutrophication potential (EP) is followed by terrestrial ecotoxicity potential (TETP), human toxicity potential (HTP) and global warming potential (GWP).

The phase in the system contributing most to the impacts is the production phase (Fig. 8), which is mainly based on the materials extraction and production processes, which require materials, energy and other resources. The end-of-life phase has minor impacts (less than 1%), as stated in the methods section, where it was assumed that materials were recycled and the LCA system had credited for them.

In order to make a better implication of the LCA findings, a comparative data from alternative ways of electricity generation and consequently emissions are provided. Turconi et al. (2013) carried out a critical review of 167 case studies including LCA of electricity generation based on hard coal, lignite, natural gas, oil, nuclear, biomass, hydroelectric, PV and wind, to identify ranges of emission data for *e.g.* GHG. Their results are represented in Table 3, showing better environmental performance of renewable resources.

Our results indicated that within the usage phase 26.90 kWh electricity output generates 1.27 kg CO_2 eq., meaning that 1 MWh would produce 47.21 kg CO_2 eq., which is coherent with the previous studies (i.e. Turconi et al., 2013). Also, Hertwich et al. (2015) confirm the environmental benefits of low-carbon energy production technologies.

5. Discussion

The results of the pilot PV net metering system installation analysed by the authors of this paper found that the annual PV energy production was 29.6% higher than the consumption of the case study facility. This deviation in the PV net metering scheme appears because significantly higher production arises from the initial goal of the investment, which was not to build a PV system that would cover the electrical energy needs of the building, but to make a profit from selling PV energy on the electricity market as guaranteed purchase within the FiT scheme. To increase the profit, a surface for mounting PV modules on the available rooftop surface of the case study entity was maximised. In Slovenia FITs are no longer in use as a consequence of a relatively low PV technology

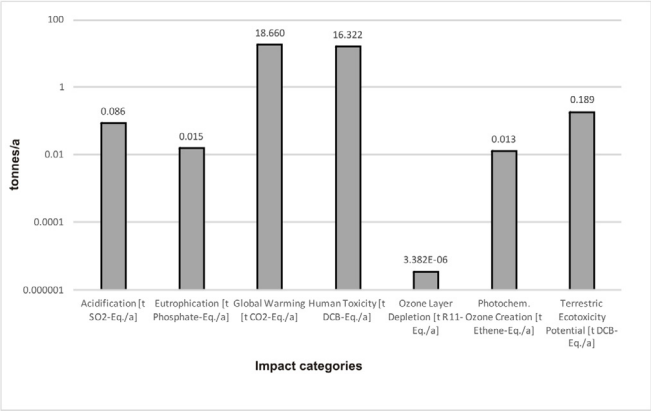

Fig. 6. Environmental impacts of the PV net metering system.

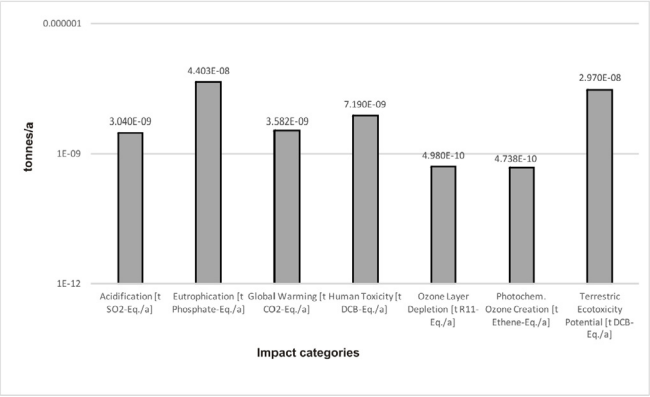

Fig. 7. Normalised environmental impacts of the PV net metering system.

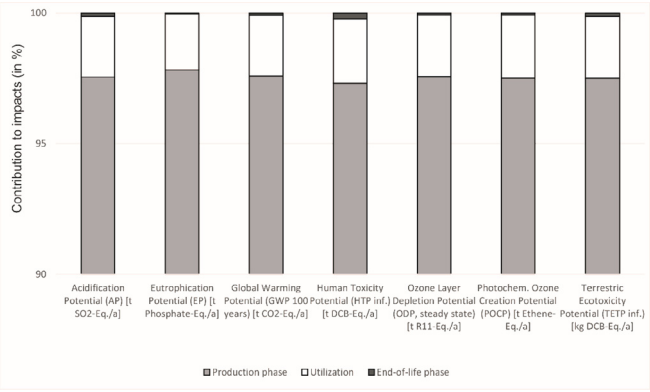
100
95
90
Contribution to impacts (in %)
Acidification Potential (AP) [t SO2-Eq./a]
Eutrophication Potential (EP) [t Phosphate-Eq./a]
Global Warming Potential (GWP 100 years) [t CO2-Eq./a]
Human Toxicity Potential (HTP inf.) [t DCB-Eq./a]
Ozone Layer Depletion Potential (ODP, steady state) [t R11-Eq./a]
Photochem. Ozone Creation Potential (POCP) [t Ethene-Eq./a]
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB-Eq./a]
Production phase
Utilization
End-of-life phase

Fig. 8. A relative contribution of different LCA phases to the total environmental impacts of the PV net metering system.

Table 3
Life cycle emissions factors for electricity generation from selected technologies, referring to the electricity output [kg/MWh], (Turconi et al., 2013).

Energy source	kg CO_2 eq.
Hard Coal	660–1050
Lignite	800–1300
Natural gas	380–1000
Oil	530–900
Nuclear power	3–35
Biomass	8.5–130
Hydropower	2–20
Solar energy	12–190
Wind	3–41

price. Therefore, new schemes have been investigated and a PV net metering scheme or procedure in now one of the more promising approaches. The idea of the PV net metering case study was to move excess energy to the time between 5.00 p.m. and 7.00 a.m. To realise this objective energy storage was needed. PV net metering uses the power grid as a "virtual" storage, as the batteries present additional cost for the investor.

Many technical solutions are possible to assure the proper working of net metering scheme not interrupting the existing meters, accessing only by the network operator. In our pilot solution, the controller for comprehensive data acquisition including possible extensions for additional sensors and higher processing speeds was chosen. These properties enable, besides basic testing of net metering and current research, also future extensions for net metering of more buildings together, fast data acquisition with feedbacks to the devices in demand side management systems including storage systems. The solution can be used as a vital part of (micro)smart grids and energy storage including comprehensive energy management and local predictions of energy production and consumption with data aggregation, privacy issues. It enables to run the algorithms that maximize self-sufficiency and limit the energy flowing to and from the grid.

When considering the environmental impacts of the PV net metering, the results indicated that the more significant environmental impacts that system's produces during its life cycle are global warming, followed by human toxicity and terrestrial ecotoxicity. The main contributors to the impacts are production processes during the manufacturing phase of the components, accounting for more than 95% of the overall impacts. This is in line with the previous studies, *e.g.* Yang et al. (2015) and Stylos and Koroneos (2014), arguing that the production of the PV modules has a significant influence on the environmental impacts and are responsible for huge GWP emissions. Also, Chen *at al.* (2016) claimed that the PV production contributed mostly to the impacts *e.g.* human toxicity, marine toxicity and material depletion. Furthermore, Stylos and Koroneos (2014) argued that the GHG emissions for all the life-cycle stages of the PV-components will decrease in the future due to improvements in manufacturing processes as well as greater efficiency of electricity production, greater durability and more effective recycling. For example, the energy efficiency varies from 10% for amorphous silicon to about 16% for cadmium telluride to 18–22% for modules based on crystalline silicon (Malandrino et al., 2017). Regarding the technology innovations Burst et al. (2016) improved the maximum voltage (V) available from the cadmium telluride (CdTe) solar cells, overcoming the limit of 1 V, offering a low cost manufacturing option with better environmental performance. Also, European Commission included PV panels in the list of Waste Electrical and Electronic Equipment (WEEE) within the EU directive (EP&EC, 2014), aiming to improve the reuse and recycling of electronic devices to contribute to resource efficiency and waste minimization (Corcelli et al., 2017). Malandrino et al. (2017) are reporting about the recycle rates for the PV modules, which were 80% the first generation module to 90–95% of the second generation modules (glass and semiconductor materials), and about several ongoing studies with emergent technologies (CIS, CIGS). PV panels also include rare materials, which will have a significant value in the future, *e.g.* projection on the basis of amount for Italy and price in 2050 is 130 million EUR for indium, over 1 billion EUR of silver, 21 million EUR of germanium and 2 billion EUR of gallium (Malandrino et al., 2017; Paiano, 2015). Thus, the producers need to consider improvements of the production processes, based on the LCA by considering circular economy concepts. Indeed, tight component and product cycles of use and reuse, aided by product design for the environment approaches help to decrease environmental impacts, wasting large amounts of embedded materials, energy, and labour (Nguyen et al., 2014).

In the utilisation (operational) phase the electricity production from the PV net metering was compared to the prevailing one in Slovenia, which is a conventional electrical energy supply from the power system using coal, gas and uranium as a fuel. Approximately one third of the electricity production in Slovenia is also from conventional hydropower plants. As mentioned in the Case study section, the energy mix production process was extracted from the Ecoinvent 2.1v database. The LCA results of this comparison are presented in Table 4. Only the results for the GWP are shown as this impact is directly linked to the energy issues, such as electricity consumption.

The results suggest that, compared to the conventional energy

Table 4
A global warming potential (GWP) for different electricity production options.

Utilisation phase	GWP 100 years [t CO_2 equiv./a]
PV net metering	0.083
Conventional energy supply	3.335

supply from the power system, PV net metering using PVs decreases the GWP by 97.5%. As argued by Stylos and Koroneos (2014) comparisons among conventional power generation units and PV-systems are supporting PV-systems as more advantageous for cleaner electricity production and that previous research with PV-installation settings confirmed a general global trend for a wide application of PV-systems. Fostering a usage of the PV net metering schemes in Slovenia, is also meaningful due the Slovenian geographical location, receiving adequate solar irradiation through the most part of the year. Based on the statistical data, an average solar irradiation per square metre of the horizontal surface in Slovenia is higher than 1000 kWh/m^2 (PV Portal, 2015). Besides reducing environmental impacts, it is expected that PV net metering would lower the total price of the electrical energy, fees and taxes per kWh in comparison to the purchase on the market, having a significant influence on motivation for an investment, which is in line with the outcomes of Stylos and Koroneos (2014) research.

When considering the willingness of the installation of new technologies, Radomes and Arango (2015) claim that in a case of Colombia high income households (or private investors) have more inclinations to invest in new, environmentally sound technologies, while low-income investors would prefer the technology with lower costs. Thus, support (also financial) for net-metering using PV at the national level is of utmost importance and it was also highlighted in China, where their policy finances technological innovations and structural upgrades of PV, which is helpful for investments (Geng et al., 2015), and crucial with regard to reversing the climate changes, currently caused with increasing carbon dioxide, methane and other GHG releases to the atmosphere. Furthermore, results from Australia showed that the uptake of small-scale solar PV systems by householder and small business owners will play a crucial role in electricity generation and where strategic agents need to support a shift to renewables (Biggs, 2016). In Slovenia, a net metering using PV and other RES is in the process of implementation.

6. Conclusions

The study of the PV net metering for a business-residential building revealed that with a proper planning of the PV power plant size the optimum balance between energy production and consumption can be achieved and consequently a minimum price per kWh of the PV net metering system can be reached, meaning that the PV net metering presents a promising option in comparison to the FiT and/or existing electricity generation from the grid. A new technical solution presented in this paper enabled the research of local net metering in real time and simultaneously including observing the impacts of solar radiation, environment temperature, temperature of PV modules on electricity production. Besides the research on the support schemes, the results suggested that the PV net metering is beneficial from the environmental perspective, especially when comparing it with the currently, conventional energy supply from the power system reducing impact on the global warming for around 40 times.

A guaranteed purchase for the first group of PV installations in 2009 will finish in 2024, and the owners will have issues with the excess of electricity after that period. However, oversized PV installations support future policies, since European Commission directives introduces producers and consumers as active players on the energy markets of the future. The owners of PV systems under FiT need to be motived to form with the near-by consumers without PV installation a smart highly energy self-sufficient community leading to smart and sustainable communities. Also, the system developed within the study enables additional upgrades of net metering system to micro grid and to establish smart grid concept managing fluctuations of RES adjusting the demand to unpredictable solar energy.

The outcomes of this study are important from several perspectives, such as supporting PV installations owners after the validity of the energy purchase contracts based on FiT, showing that net metering can present a financially reasonable option for the investors, also in a case of future increases of electricity price (EUR/kWh on their bill). The manufacturing process of the PV-modules still represents a major contribution to the environmental impacts, however the PV net metering if properly priced and incentivized can help to accelerate the transition to equitable, sustainable, post-fossil carbon societies and does promise cleaner energy production and consumption, especially when making a comparison with conventional production. The paper also provides insightful recommendations for Slovenian policy makers as well as for independent citizens, who wish to support the activities for our sustainable future.

Acknowledgements

The authors would like to thank two anonymous reviewers, prof. Don Huisingh, prof. Rodrigo Lozano, and emeritus prof. Peter Glavič for their constructive and valuable comments, suggestions and directions in improving the earlier versions of this manuscript. Many thanks also to dr. Angela Carpenter for carrying out a proofread of the manuscript and her amendments. Further, the authors would like to thank the European Commission its Interreg MED Programme for partially funding the research within the project PV-NET, reference number: IC-MED-12-68.

References

Abdin, G.C., Noussan, M., 2018. Electricity storage compared to net metering in residential PV applications. J. Clean. Prod. 176, 175–186. https://doi.org/10.1016/j.cleapro.2017.12.132.

Azapagic, A., Clift, R., 1999. Life cycle assessment and multiobjective optimisation. J. Clean. Prod. 7 (2), 135–143. https://doi.org/10.1016/S0098-1354(99)00308-7.

Biggs, C., 2016. A resource-based view of opportunities to transform Austrialia's electricity sector. J. Clean. Prod. 123, 203–217. https://doi.org/10.1016/j.jclepro.2015.12.006.

Burst, J.M., Duenow, J.N., Albin, D.S., Colegrove, E., Reese, M.O., Aguiar, J.A., Jiang, C.-S., Patel, M.K., Al-Jassim, M.M., Kuciauskas, D., Swain, S., Ablekim, T., Lynn, K.G., Metzger, W.K., 2016. CdTe solar cells with open-circuit voltage breaking the 1 V barrier. Nature Energy 1, 16015. https://doi.org/10.1038/nenergy.2016.15.

Camello, S., Reichelstein, 2017. Cost competitiveness of residential solar PV: the impact of net metering restrictions. Renew. Sustain. Energy Rev. 75, 46–57. https://doi.org/10.1016/j.rser.2016.10.050.

Chen, W., Hong, J., Yuan, X., Liu, J., 2016. Environmental impact assessment of monocrystalline silicon solar photovoltaic cell production: a case study in China. J. Clean. Prod. 112, 1025–1032. https://doi.org/10.1016/j.jclepro.2015.08.024.

Corcelli, F., Ripa, M., Ulgiati, S., 2017. End-of-life treatment of crystalline silicon photovoltaic panels. An emergy-based case study. J. Clean. Prod. 161, 1129–1142.

Couture, T.D., Cory, K., Williams, E., 2010. A Policymaker's Guide to Feed-in-tariff Polcy Design. NREL Tech. Reports. NREL/TP-6A2-44849.

Darghouth, N.R., Barbose, G., Wiser, R.H., 2014. Customer-economics of residential photovoltaic systems (Part 1): the impact of high renewable energy penetrations on electricity bill savings with net metering. Energy Pol. 67, 290–300. https://doi.org/10.1016/j.enpol.2013.12.042.

Dones, R., Bauer, C., Bollige, R., Burger, B., Heck, T., Röder, A., Scherrer, P., Faist Emmenegger Faist, M., Frischknecht, R., Jungbluth, N., Tuchschmid, M., 2007. Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and Other UCTE Countries. Swiss Centre for Life Cycle Inventories

and Ecoinvent Centre. Ecoinvent Report No.5. Villigen and Ulster. December 2007.
Dufo-Lopez, R., Bernal-Agustín, J.L., 2015. A comparative assessment of net metering and net billing policies. Study cases for Spain. Energy 84, 684–694. https://doi.org/10.1016/j.energy.2015.03.031.
Eid, C., Guillén, J.R., Marín, P.F., Hakvoort, R., 2014. The economic effect of electricity net-metering with solar PV: consequences of network cost recovery, cross subsidies and policy objectives. Energy Pol. 75, 244–254. https://doi.org/10.1016/j.enpol.2014.09.011.
European Parliament and European Council (EP&EC), 2009. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources, Official Journal of the European Union, 5 June, 2009.
European Parliament and the European Council (EP&EC), 2014. Directive 2012/12/EU of the European Parliament and of the Council of 4th July 2012 on Aste Electrical and Electronic Equipment (WEEE) (Recast). (Accessed 4 July 2014).
Euroobserv'er, 2017. Photovoltaic Barometer, April, 2017. Available online (April 2018): file:///C:/Users/rebeka.kovacic/Downloads/EurObservER-Photovoltaic-Barometer-2017-EN.pdf.
European Commission (COM), 2013. European Commission guidance for the design of renewables support schemes. Accompanying the document Communication from the Commission. Delivering the internal market in electricity and making the most of public intervention. SWD (2013) 439 final, Brussels, 5. 11. 2013.
European Commission (COM), 2014. Communication from the Commission to the European Parliament, the Council, the European economic and social committee and the Committee of the Regions. A policy framework for climate and energy in the period from 2020 to 2030, COM (2014) 15 final, Brussels, 22. 1. 2014.
Eurostat, 2015a. News Release. Environment in the EU. Each Person in the EU Generated 481 Kg of Municipal Waste in 2013. Eurostat Press Office. (Accessed 26 March 2015).
Eurostat, 2015b. Energy from renewable sources. Available online (December 2015): http://ec.europa.eu/eurostat/web/energy/data/shares.
Eurostat, 2018. Share of Renewable Energy in Gross Final Energy Consumption. Available online (June 2018). http://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&language=en&pcode=t2020_31&plugin=1.
Every, Jeremy, Li, Li, Dorrell David, G., 1 September 2017. Leveraging smart meter data for economic optimization of residential photovoltaics under existing tariff structures and incentive schemes. Appl. Energy 201, 158–173. https://doi.org/10.1016/j.apenergy.2017.05.021.
Fikru, M.G., Gelles, G., Ichim, A.-M., Kimball, J.W., Smith, J.D., Zawodnoik, M.J., 2018. An economic model for residential energy consumption, generation, storage and reliance on cleaner energy. Renew. Energy 119, 429–438.
Frischknecht, R., Jungbluth, N., 2007. In: Althaus, H.-J., Bauer, C., Doka, G., Dones, R., Hischier, R., Hellweg, S., Humbert, S., Köllner, T., Loerincik, Y., Margni, M., Nemecek, T. (Eds.), Implementation of Life Cycle Impact Assessment Methods. Swiss Centre for Life Cycle Inventories, Dübendorf. Data v2.0, Ecoinvent report No. 3.
Geng, B., Zhang, X., Liang, Y., Bao, H., 2015. Do favourable land price policy affect renewable industry? Evidence from photovoltaic. J. Clean. Prod. 1–9. https://doi.org/10.1016/j.jclepro.2015.08.062. XX.
Guinée, J.B., 2001. In: Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.A., de Bruijn, H., van Duin, R., Huijbregts, M.A.J., Lindeijer, E., Roorda, A.A.H., Weidema, B.P. (Eds.), Life Cycle Assessment; an Operational Guide to the ISO Standards; Parts 1 and 2. Ministry of Housing, Spatial Planning and Environment (VROM) and Centre of Environmental Science (CML). Den Haag and Leiden, The Netherlands.
Hertwich, E.G., Gibon, T., Bouman, E.A., Arvsen, A., Suh, S., Heath, G.A., Bergsen, J.D., Ramirez, A., Vega, M.I., Shi, L., 2015. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. Proc. Natl. Acad. Sci. Unit. States Am. 19, 6277–6282. https://doi.org/10.1073/pnas.1312753111.
PE International, 2008. http://www.gabi-software.com/.
ISO, 2006a. Environmental Management – Life Cycle Assessment – Principles and Framework. International Organization for Standardization, Geneva. ISO 14040.
Koumparou, I., Christoforidis, G.,C., Efthymiou, V., Papagiannis, G.,K., Georghiou, G.,E., 2017. Configuring residential PV net-metering policies – a focus om the Mediterranean region. Renew. Energy 113, 795–812. https://doi.org/10.1016/j.renene.2017.06.051, 2017.
Malandrino, O., Sica, D., Testa, M., Supino, S., 2017. Policies and measures for sustainable management of solar panel end-of-life in Italy. Sustainability 9, 1–15. https://doi.org/10.3390/su9040481, 481.
Nguyen, H., Stuchtey, M., Zils, M., 2014. Remaking the Industrial Economy. McKinsey Quarterly. Feb, 2014. Available online (December 2015): http://www.mckinsey.com/insights/manufacturing/remaking_the_industrial_economy.
Nikolaidis, A.I., Milidonis, A., Charalambous, C.A., 2015. Impact of fuel-dependent electricity retail charges on the value of net-metered PV application. Energy Policy 84, 684–694. https://doi.org/10.1016/j.enpol.2015.01.010.
Nikolaidis, A.I., Charalambous, C.A., 2017. Hidden financial implications of the net energy metering practice in an isolated power system: critical review and policy insights. Renew. Sustain. Energy Rev. 77, 706–717. https://doi.org/10.1016/j.rser.2017.04.032.
Oliva, S.H., 2018. Assessing the growth of residential PV exports with energy efficiency and the opportunity for local generation network credits. Renew. Energy 121, 451–459. https://doi.org/10.106/j.renene.2018.01.007.
Paiano, A., 2015. Photovoltaic waste management in Italy. Renew. Sustain. Energy Rev. 41, 99–112 ([CrossRef]).
Peters, J.F., Baumann, M., Zimmermann, B., Braun, J., Weil, M., 2017. The environmental impact of Li-Ion batteries and the role of key parameters – a review. Renew. Sustain. Energy Rev. 67, 491–506. https://doi.org/10.1016/j.rser.2016.08.039.
Poullikkas, A., 2013. A comparative assessment of net metering and feed in tariff schemes for residential PV systems. Sustainable Energy Technologies and Assessment 3, 1–8. https://doi.org/10.1016/j.seta.2013.04.001.
PV Portal – A Slovenian Portal for Photovoltaic, 2015. A Solar Radiation in Slovenia. Available online (June 2015): http://pv.fe.uni-lj.si/ObsSLO.aspx (In Slovene).
Radomes Jr., A.A., Arango, S., 2015. Renewable energy technology diffusion: an analysis of photovoltaic-system support schemes in Medellín, Colombia. J. Clean. Prod. 92, 152–161. https://doi.org/10.1016/j.jclepro.2014.12.090.
Ramírez, F.J., Honrubia-Escribano, A., Gómez-Lázaro, E., Pham, D.T., 2017. Combining feed-in-tariffs and net-metering schemes to balance development in adoption of photovoltaic energy: comparative economic assessment and policy implications for European Countries. Energy Pol. 102, 440–452.
Ratnam, E.L., Weller, S.R., Kellett, M.C., 2015. Scheduling residential battery storage with solar PV: assessing the benefits of net metering. Appl. Energy 155, 881–891. https://doi.org/10.1016/j.apenergy.2015.06.061.
Rocha, L.C.S., Aquilla, G., de Oliveira Pamplona, E., de Paiva, A.P., 2017. Galelli chieregatti, B., and de Sa Brasil Lima. J. Clean. Prod. 168, 1448–1462.
Slovenian Energy Agency of Slovenia, 2016. Report on the State of the Energy Sector in Slovenia in. Available online (June 2018).
Strupeit, L., Palm, A., 2015. Overcoming barriers to renewable energy diffusion: business models for consumer-sited solar photovoltaics in Japan, Germany and the United States. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2015.06.120. Article (in press).
Stylos, N., Koroneos, C., 2014. Carbon footprint of polycrystalline photovoltaic systems. J. Clean. Prod. 64, 639–645.
Thinkstep, 2015. Description of the CML 2001 Method. Available online (June 2015): http://www.gabi-software.com/america/support/gabi/gabi-lcia-documentation/cml-2001/.
Turconi, R., Bodrin, A., Astrup, T.F., 2013. Life cycle assessment (LCA) of electricity generation technologies: overview, comparability and limitations. Renew. Sustain. Energy Rev. 28, 555–565. https://doi.org/10.1016/j.rser.2013.08.013.
UN Department of Economic and Social Affairs (UNDESA), 2013. World Economic and Social Survey 2013. Sustainable Development Challenges. United Nations, New York, 2013.
Virtič, P., Mrak, P., Koumparou, I., Hadjipanayi, M., Papagiannis, G., Christoforidis, G.C., de la Rosa, P., Oliveira, J., Martins, W., Charalambous, A., Poize, N., Kovačič Lukman, R., Georghiou, G.E., 2014. Solar energy and net metering in the Mediterranean area (the PVNET project). In: Kovačič Lukman, R., Glavič, P., Koletnik, D., Virtič, P., Horvat, B. (Eds.), 17th European Round Table on Sustainable Consumption and Production - ERSCP, Slovenia. Coference Proceedings, Nigrad, 2014, pp. 983–988.
Watts, D., Valdés, M.F., Jara, D., Watson, A., 2015. Potential residential PV development in Chile: the effect of Net metering and Net Billing schemes for grid-connected PV systems. Renew. Sustain. Energy Rev. 41, 1037–1051. https://doi.org/10.1016/j.rser.2014.07.201.
Wegener Sleeswijk, A., Van Oers, L.F.C.M., Guinée, J.B., Struijs, J., Huijbregts, M.A.J., 2008. Normalisation in the product life cycle assessment: an LCA of the global and European economic systems in the year 2000. Sci. Total Environ. 390 https://doi.org/10.1016/j.scitotenv.2007.09.040, 277–240.
Yamamoto, Y., 2012. Pricing electricity from residential photovoltaic systems: a comparison of feed-in tariff, net metering, and net purchase and sale. Sol. Energy 86, 2678–2685. https://doi.org/10.1016/j.solener.2012.06.001.
Yang, D., Liu, J., Yang, J., Ding, N., 2015. Life-cycle assessment of China's multicrystalline silicon photovoltaic modules considering international trade. J. Clean. Prod. 94, 35–45. https://doi.org/10.1016/j.jclepro.2015.02.003.